Comparisons of CFD Solutions of Static and Maneuvering Fighter Aircraft with Flight Test Data

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Overview

Application of CFD to aircraft stability & control (S&C)

- Background
- Air Force SEEK EAGLE Office (AFSEO)
- The problem…
- Suggested approach
- Examples:
  - Static: F-16XL (CAWAPI) / F-18
  - Maneuvering: F-16C
- Conclusion

Background

- Virtually every new a/c and armament program encounters unexpected S&C problems
  - Current S&C modeling techniques inadequate
  - Complex S&C issues require nonlinear, CFD-in-the-loop simulations with control surfaces modeled
- New CFD methods combined with HPC resources ...
  - address S&C problems that previously were untenable
  - overcome experimental gaps
  - complement experiments
  - result in safer flight testing
  - reduce amount of wind tunnel and/or flight testing

Saab JAS39 “Gripen”

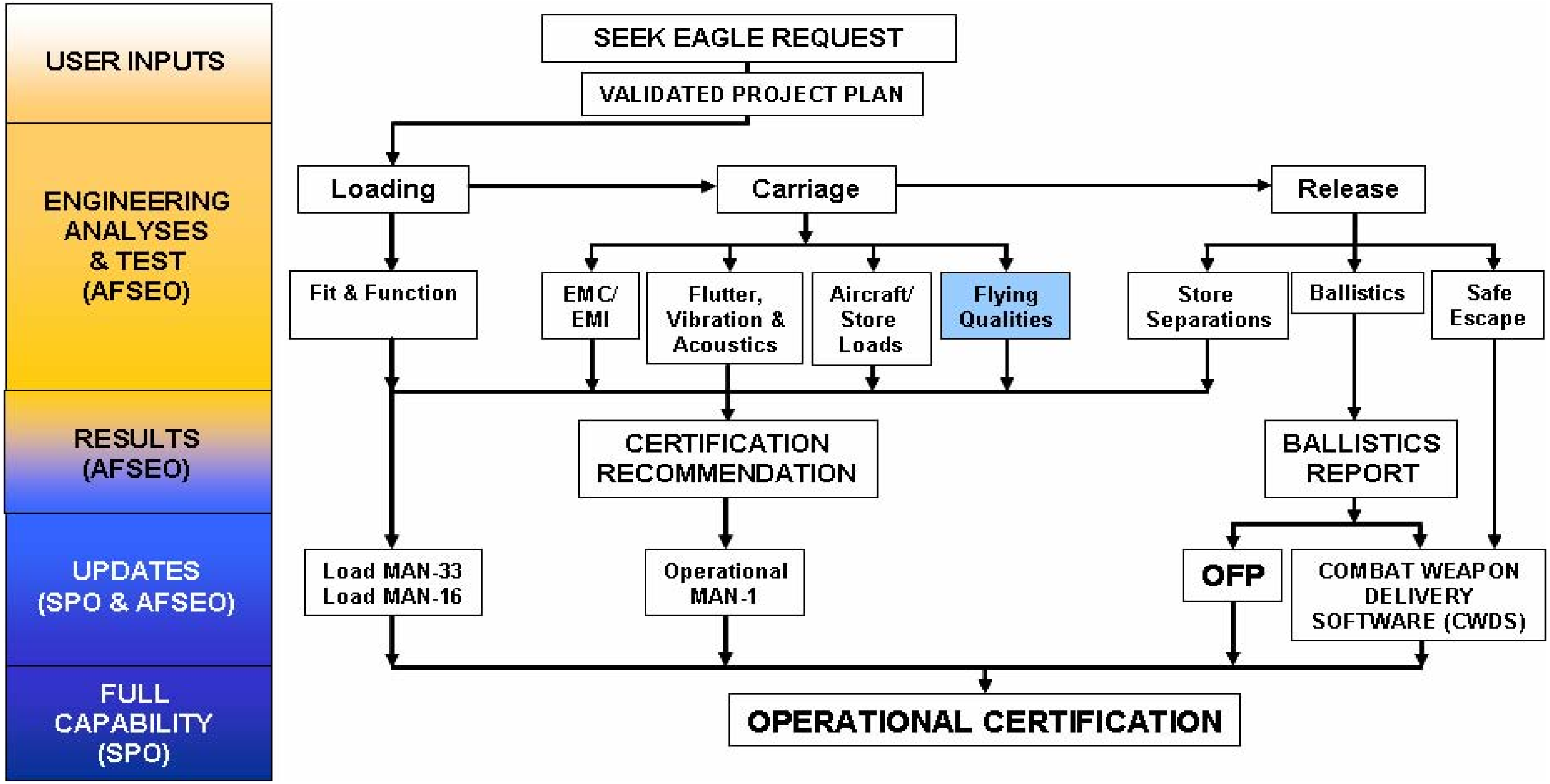
Store separation test

Play

Computational S&C Approaches

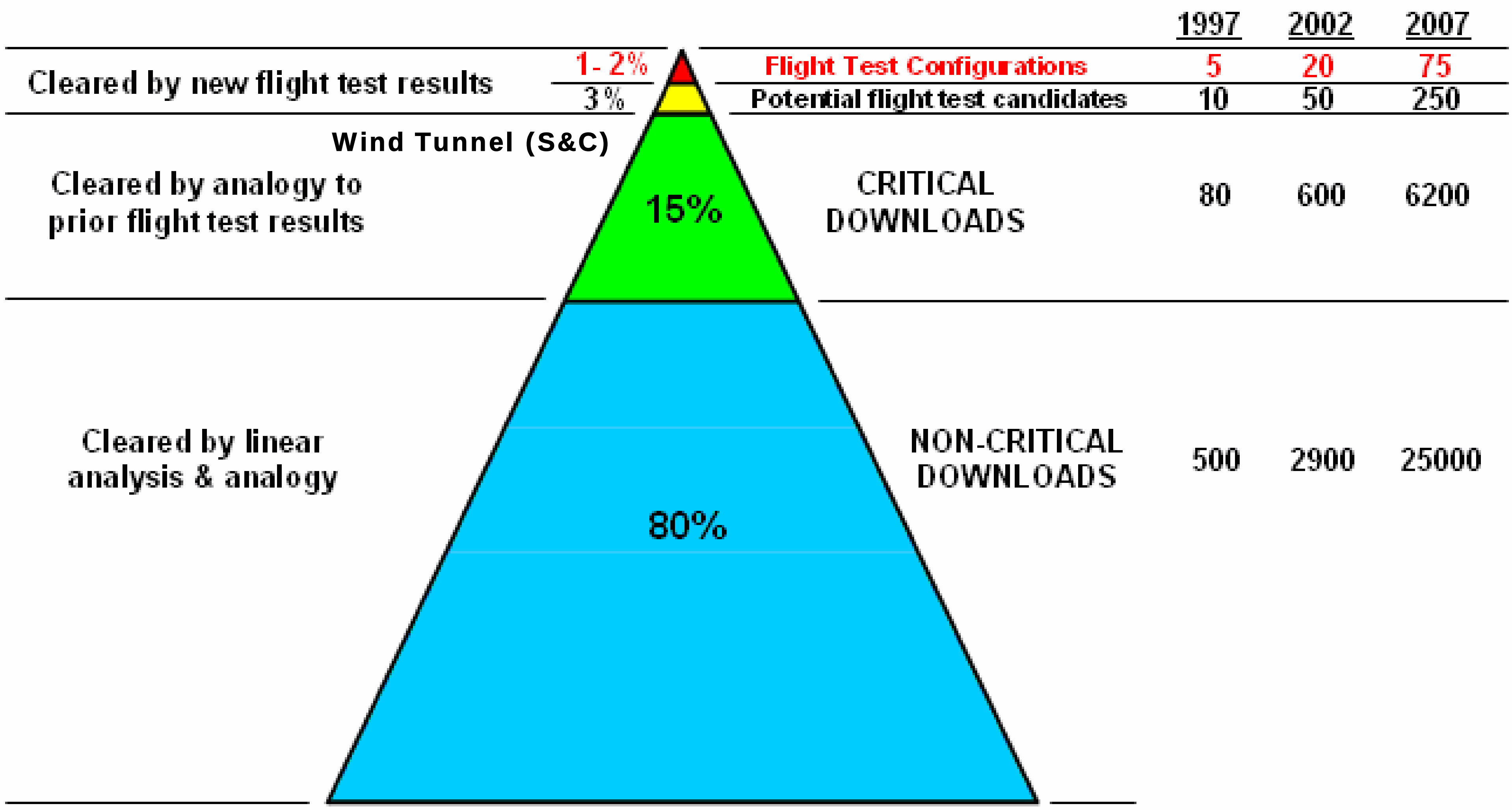
- "Brute-force" approach to filling an aerodynamic database (Murman *et al*, Rogers *et al*)
  - 30,000 solutions → 256 procs/16 mill cells → 158 years
  - Only static data at discrete points
- Data fusion approach (Tang *et al*)
  - Intelligent agents to combine low/high order solutions
- Automated Cartesian-based methods (Murman)
- Reduced-frequency approach to dynamic derivatives (Murman)
- Many, many others...
- New RTO task group → AVT 166

USAF SEEK EAGLE Office (AFSEO)



- The SEEK EAGLE program is the standard for the aircraft-stores certification process for the US Air Force
- Provides Quick Reaction Certifications (QRC), Certification Recommendations (CR), and Flight Clearances (FC)

The AFSEO Problem...



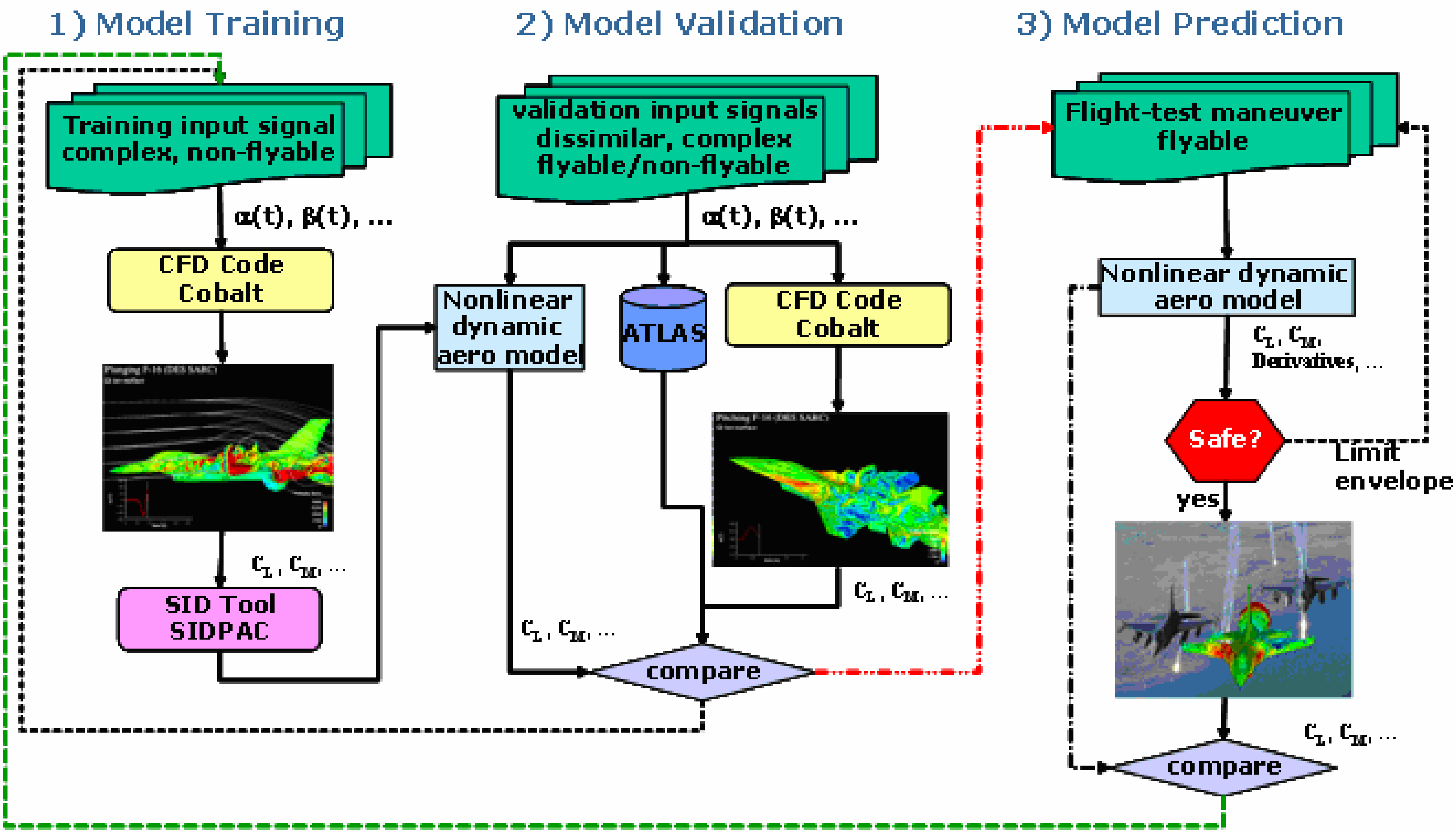
...and Other Issues

- F-16 and F-22 ATLAS aerodynamic database limitations:
  - Limited in the number of configurations
  - Only symmetric configurations available
  - No data for modern stores and suspension equipment
- Unable to predict where instabilities occur in the flight envelope (if at all)
- Long history of flight test programs where lots of $$ spent to find ...... absolutely nothing

Suggested Approach

- Focus on specific flight conditions (if possible)
- Simulate closed-loop, full-scale a/c at critical conditions with a single, complex and efficient maneuver (possibly non-flyable)
- Generate nonlinear, dynamic reduced-order models for aerodynamic loads
- Use model for S&C analysis, flight simulation, control system design, etc.
  - Continuous data
  - Derivatives computed analytically
  - Allows SEEK EAGLE Office flexibility to handle any new configuration and independence from contractors

Suggested Approach



Examples

Flow Solver - *Cobalt*

Numerical Modeling

- Unstructured, cell-centered, finite volume CFD code
- Hybrid grids (arbitrary elements), overset grids
- Space discretization:
  - Godunov's first-order accurate exact Riemann solver
  - Second-order accuracy through least-squares reconstruction
- Time discretization:
  - Point-implicit with Newton sub-iterations for time accuracy
- 6DOF and ALE for rigid body motion

Physical Modeling

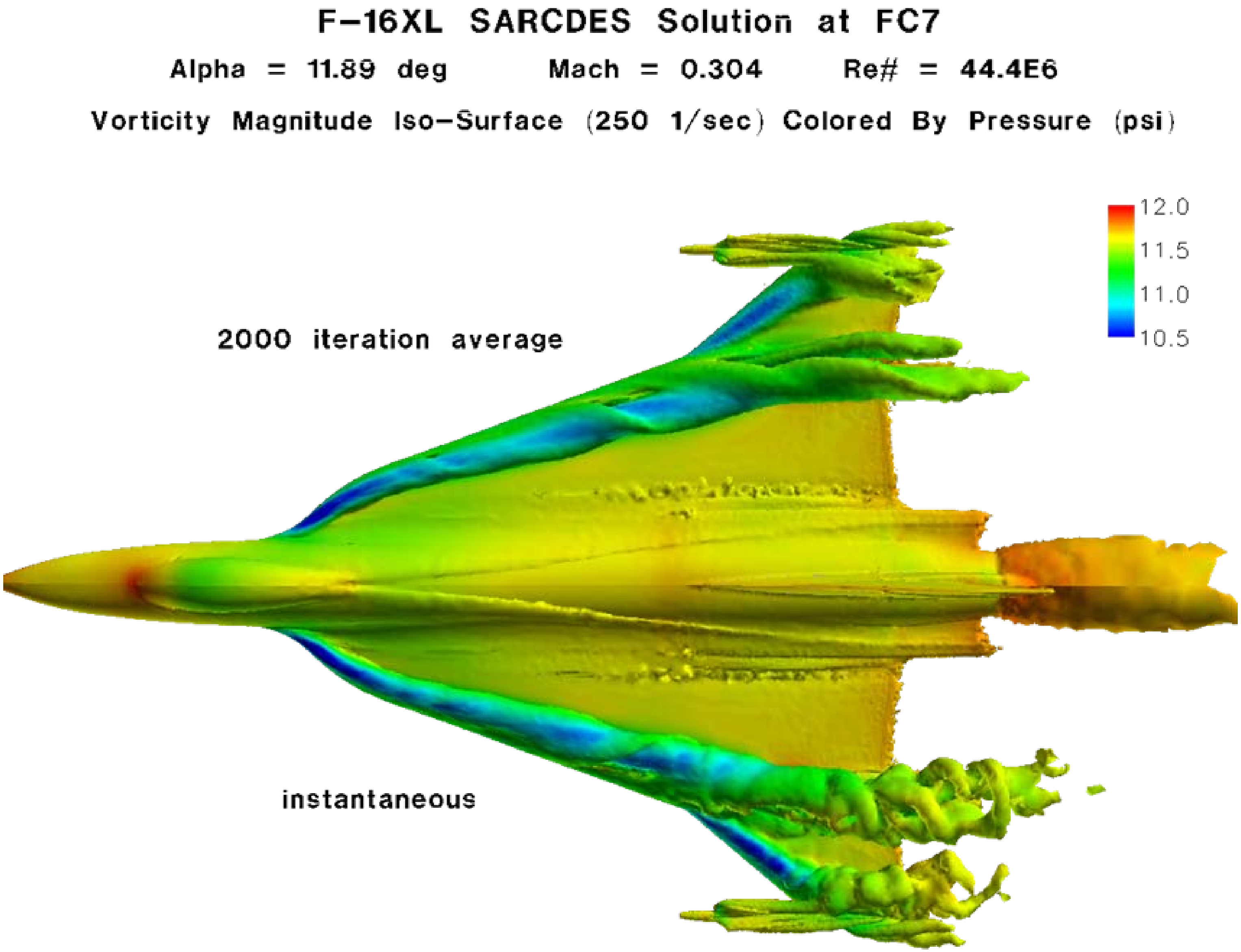
- Compressible Euler and NS, laminar and RANS
- Equilibrium air physics
- Turbulence models:
  - Spalart-Allmaras (SA)
  - Mentor's SST
  - Wilcox's 1998 k-ω
  - Detached Eddy Simulation (DES) for S-A and SST
  - Curvature corrections (SARC)

F-16XL

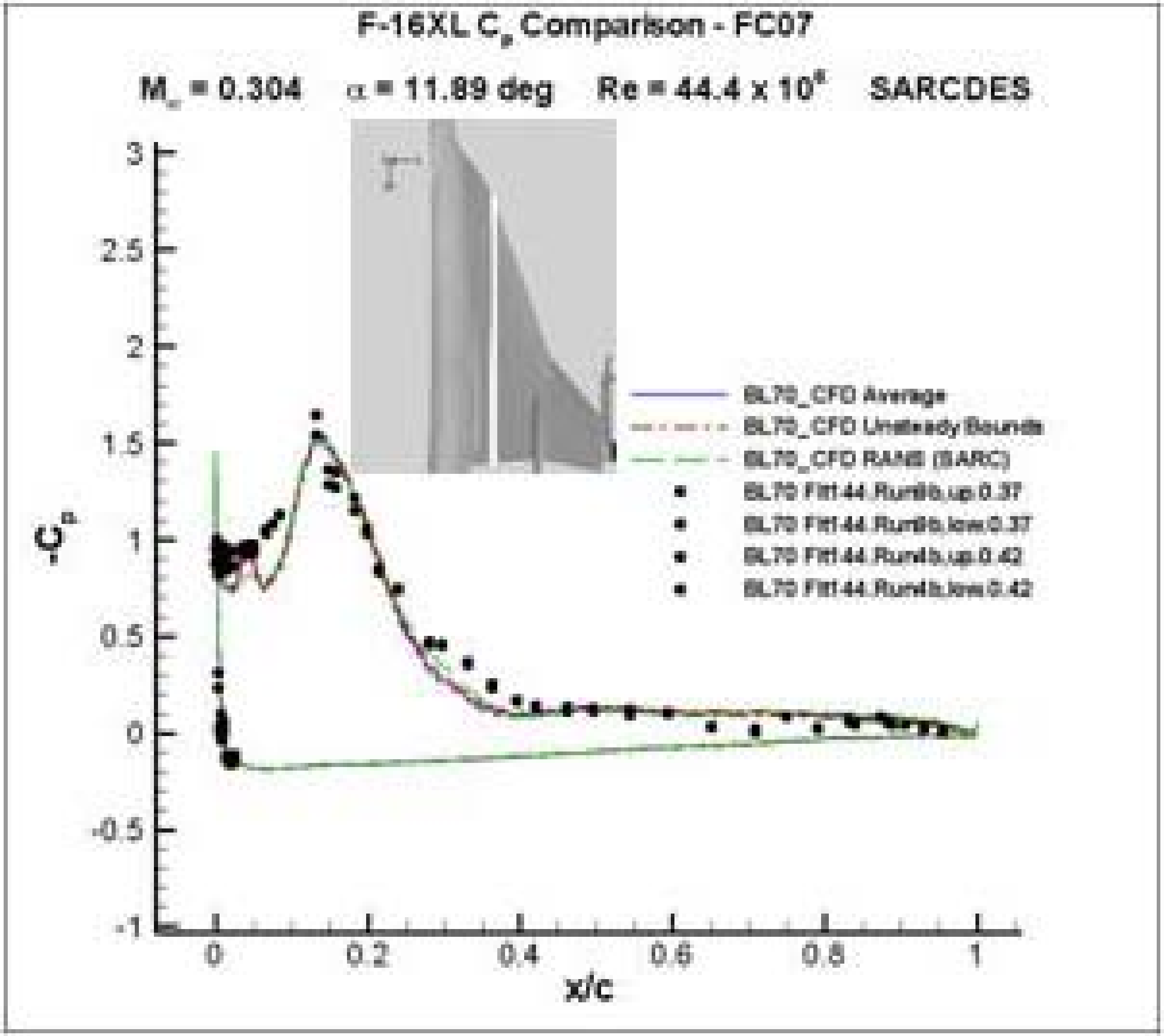
- RTO AVT-113 (CAWAPI)
- Comprehensive validation of CFD methods against available flight test database
- Time-accurate DES calculations at full-scale flight Reynolds numbers

Morton, S.A., McDaniel, D.R., and Cummings, R.M., "F-16XL Unsteady Simulations for the CAWAPI Facet of RTO Task Group AVT-113," AIAA Paper 2007-0493, Jan. 2007.

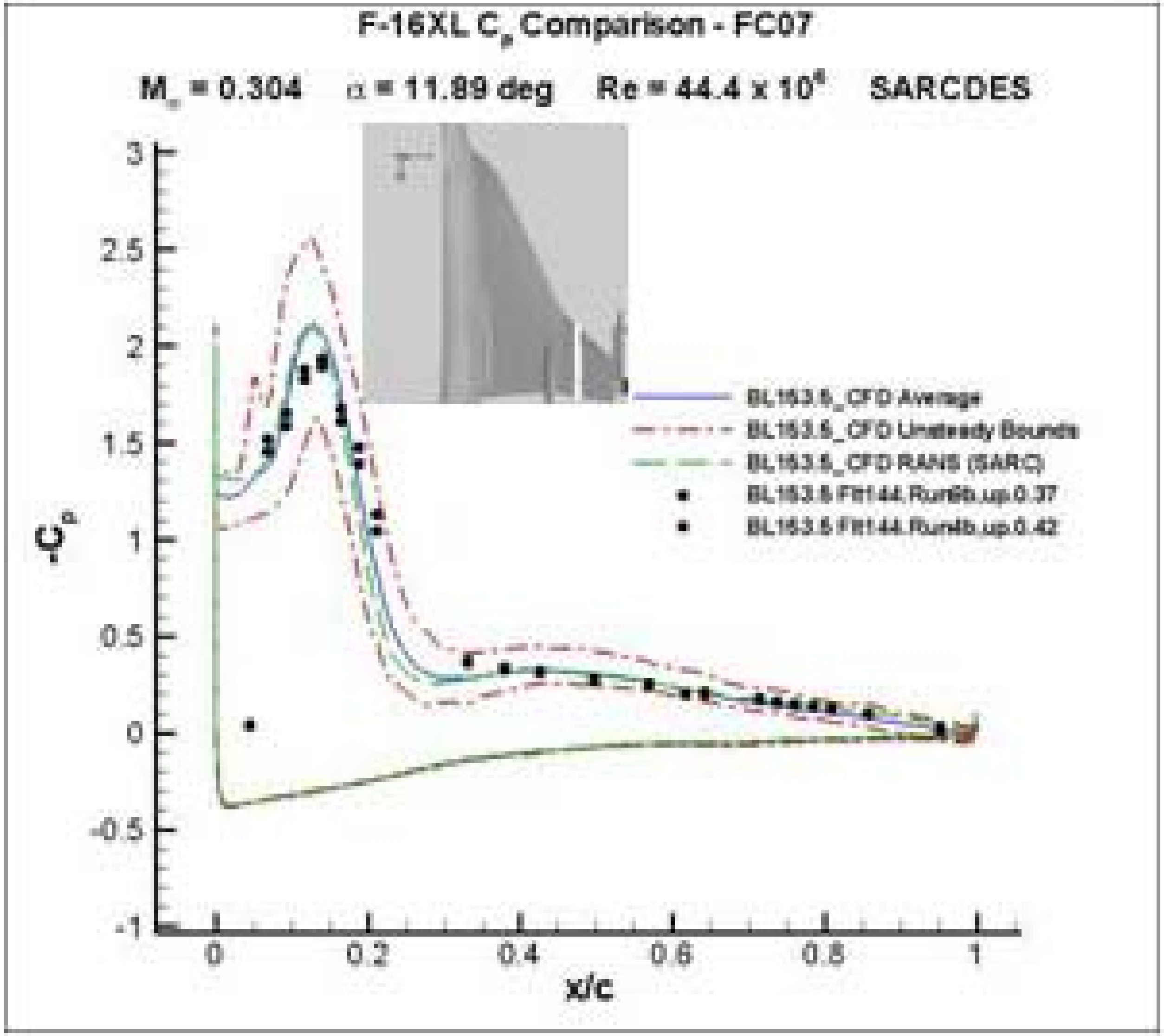
F-16XL (CAWAPI)



F-16XL (CAWAPI)

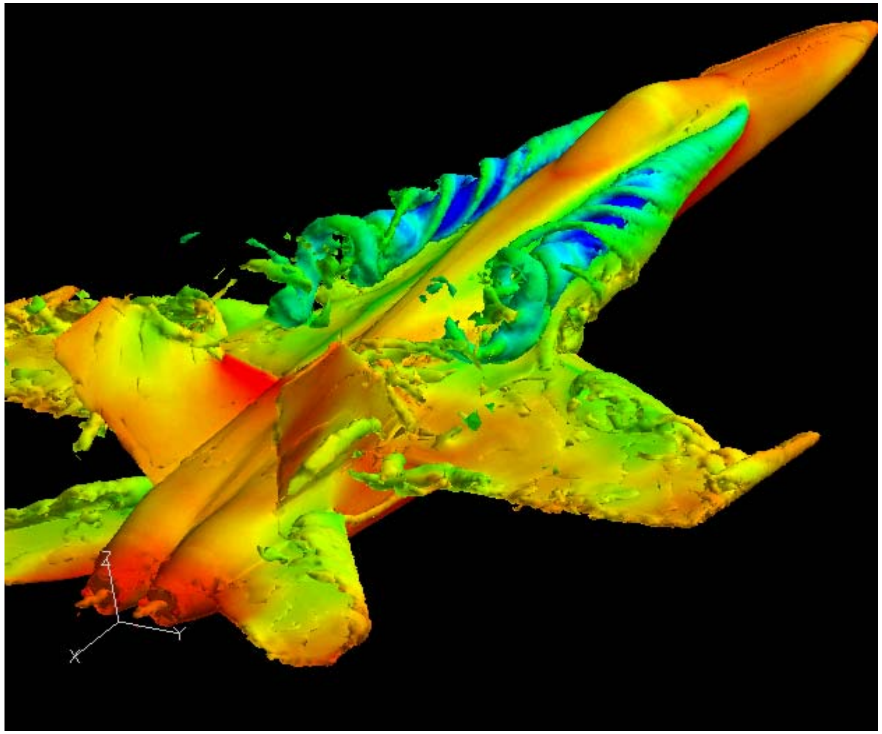


F-16XL (CAWAPI)



F-18C (HARV)

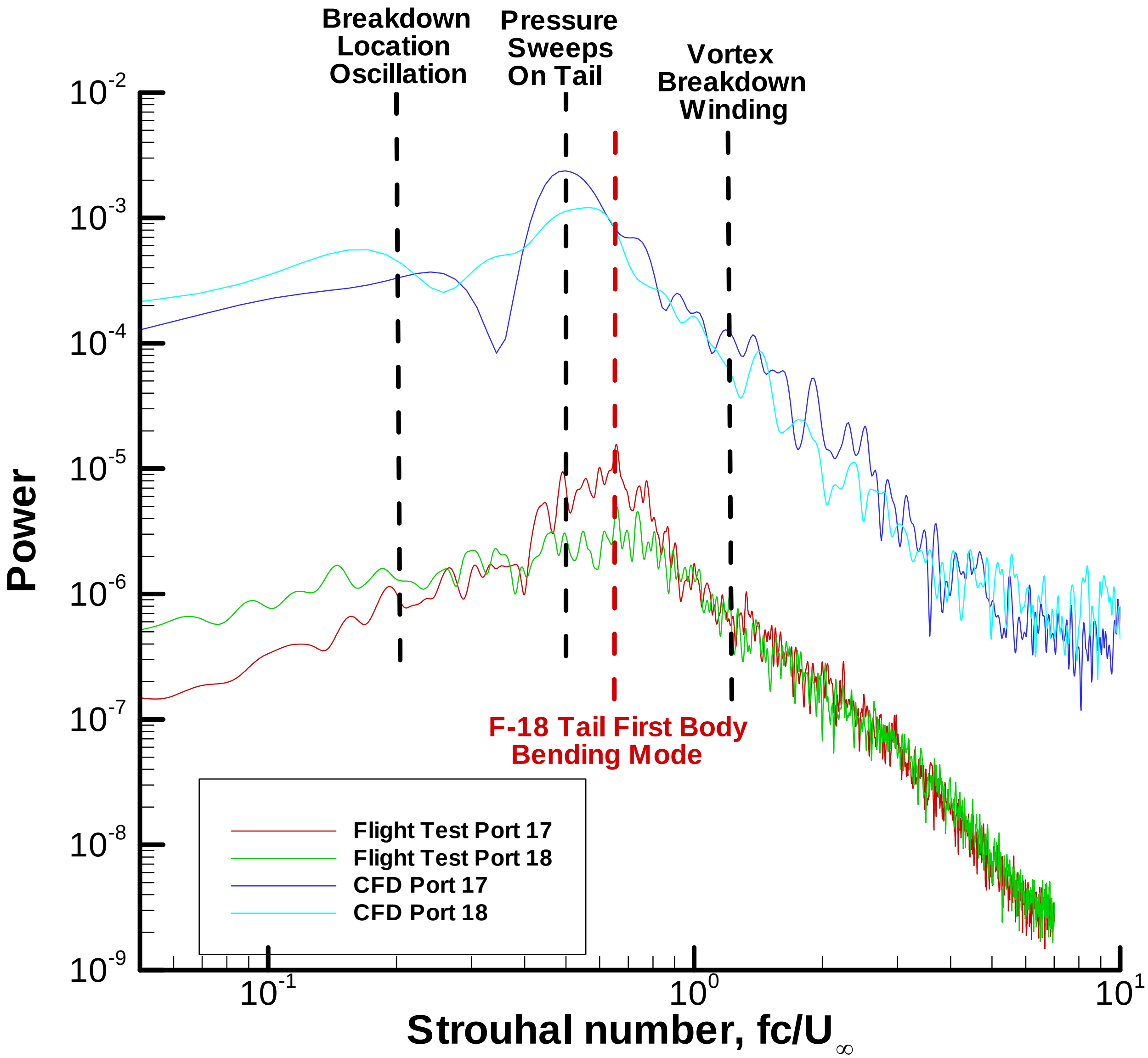
- High Angle of Attack Research Vehicle (HARV) – NASA-Dryden
- Rich source of flow viz, surface pressures, and aeroelastic data
- Numerical investigation to try and accurately predict flow impinging on vertical tails (M=0.28, Re#=13E6, α=30 deg)



Morton, S.A., Cummings, R.M., and Kholodar, D.B., "High Resolution Turbulence Treatment of F/A-18 Tail Buffet," AIAA Paper 2004-1676, April 2004.

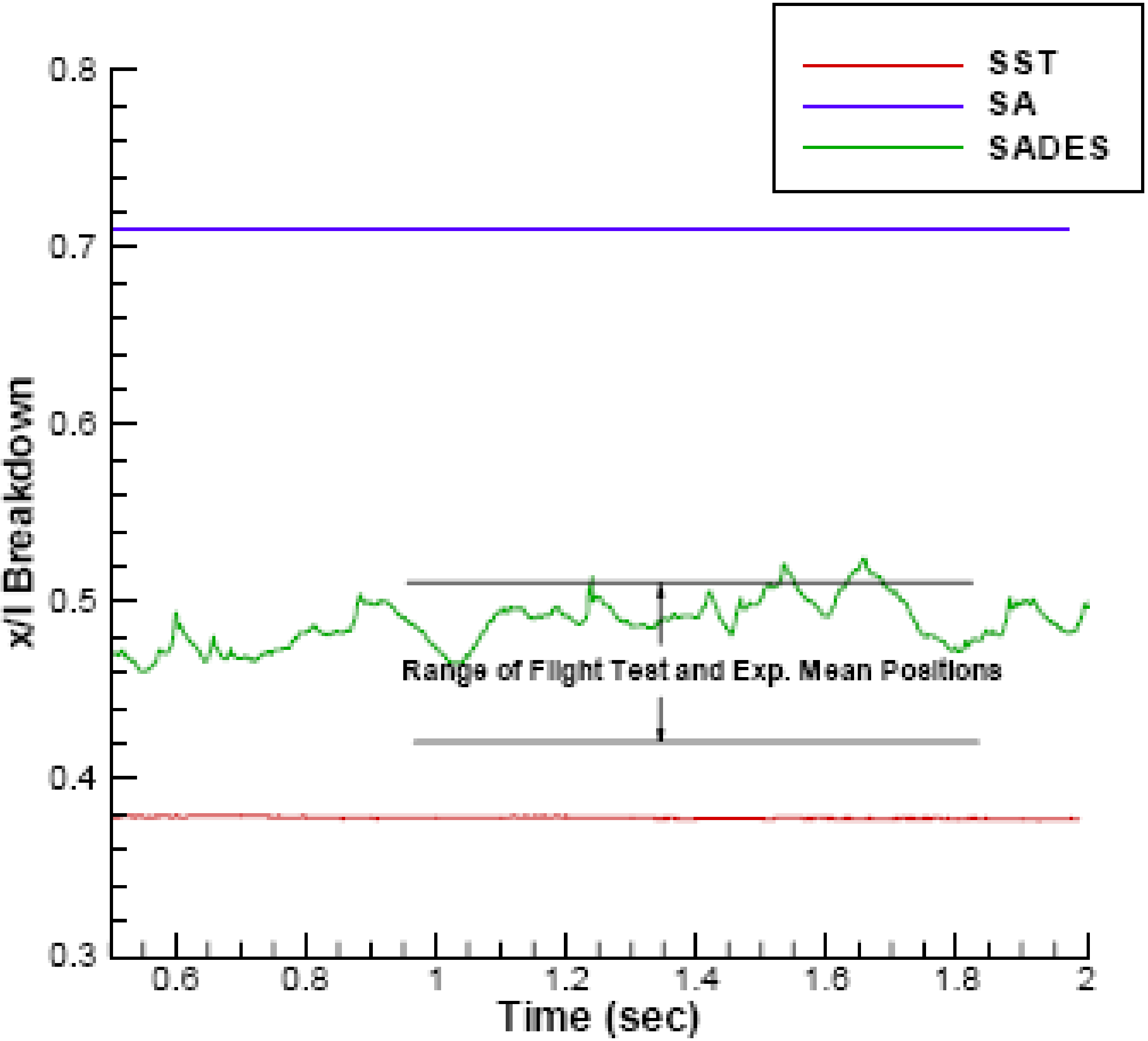
Play Play

F-18C (HARV)



Breakdown Location Oscillation
Pressure Sweeps On Tail
Vortex Breakdown Winding
F-18 Tail First Body Bending Mode
Power
Strouhal number, fc/U∞
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-1
10^0
10^1
Flight Test Port 17
Flight Test Port 18
CFD Port 17
CFD Port 18

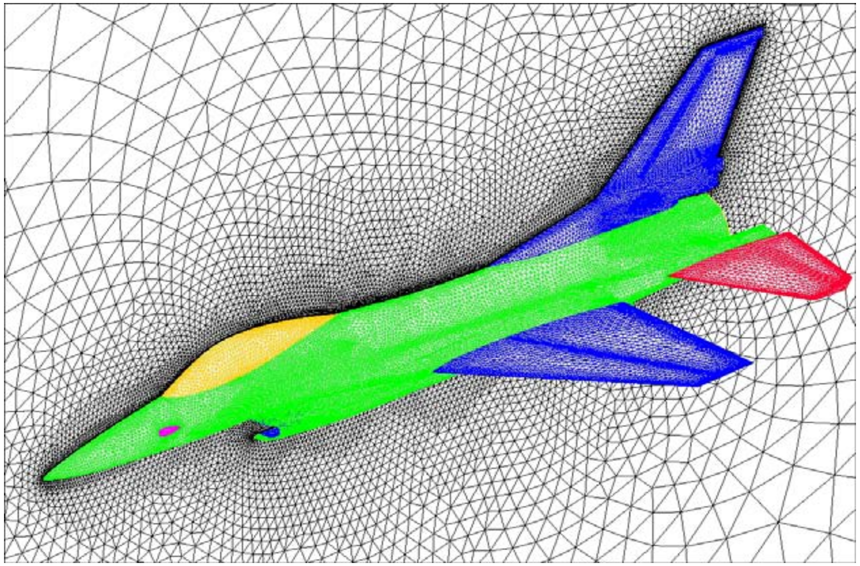
F-18C (HARV)

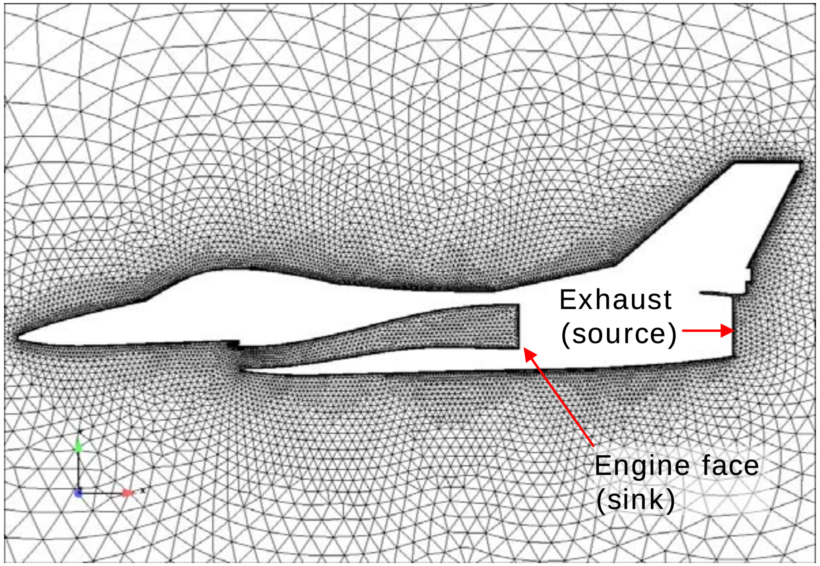


SST
SA
SADES
0.8
0.7
0.6
0.5
0.4
0.3
x/l Breakdown
Range of Flight Test and Exp. Mean Positions
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Time (sec)

Full-Scale F-16C Motion Simulations

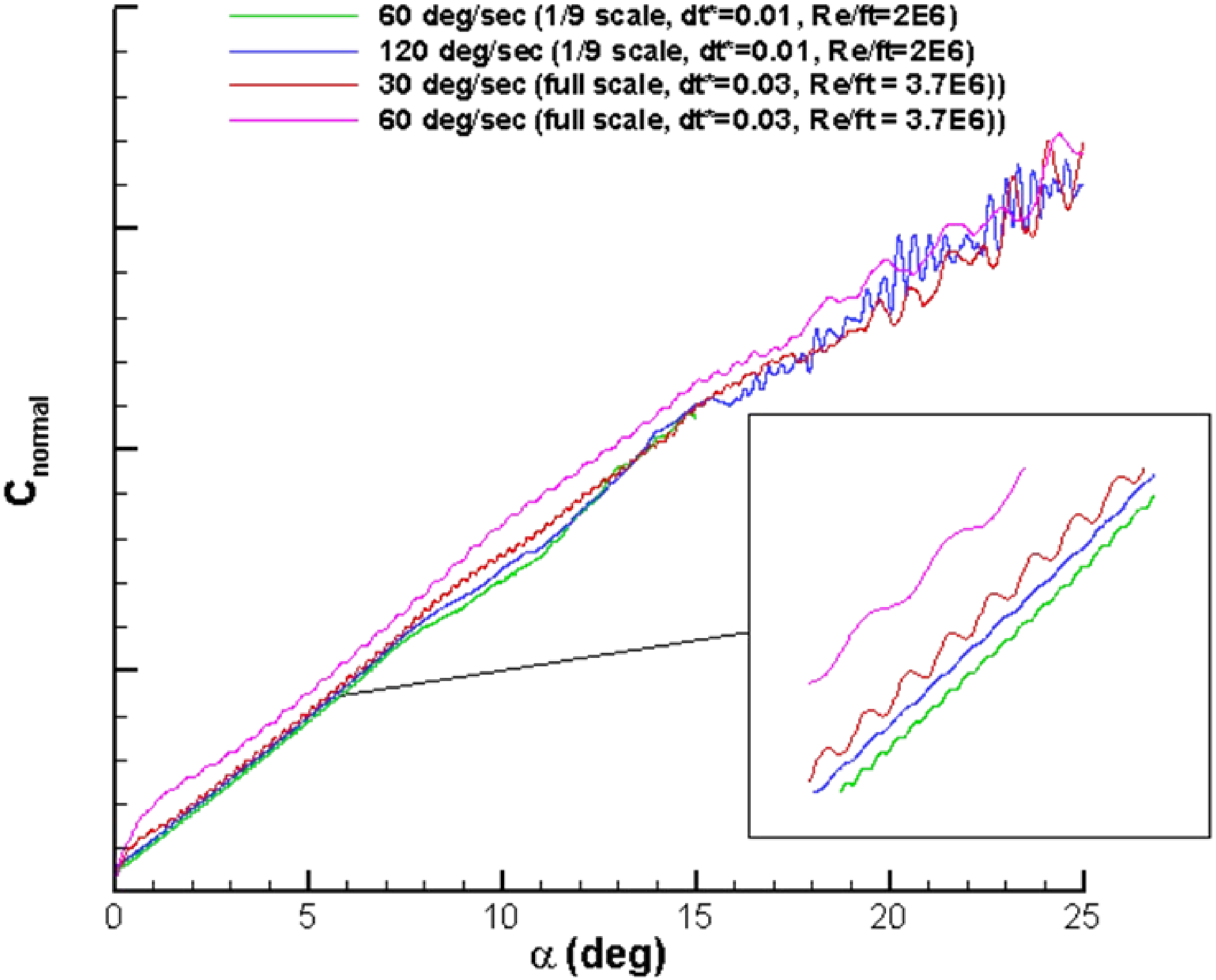
- Half-span grid with 3.4 x 10^6 cells and prismatic layers
- Cells concentrated in the strake vortex
- Forebody bump, diverter, ventral fin modeled
- Engine mass flow modeled
- Flow conditions:
  - M_∞ = 0.25/0.60
  - Re=14.7 x 10^6/42 x 10^6
- Numerical parameters:
  - Δt=0.0004s/0.0002s (Δt^*=0.01)
  - 5 Newton sub-iterations
  - DES based on SA with RC





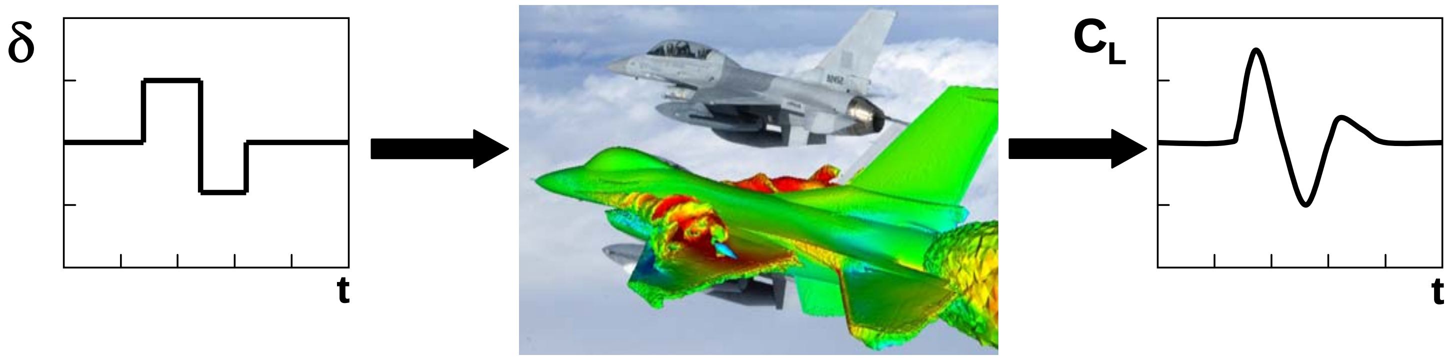
α-Sweeps & Dynamic Scale Effects

- Angle of attack sweeps at various pitch rates



Aircraft System Identification (SID)

- Normally applied to flight-test data to generate aerodynamic models (assumed time-invariant)
- Can use SID techniques to analyze CFD data computed for aircraft in prescribed motion
- **S**ystem **Id**entification **P**rograms for **A**ir**c**raft (SIDPAC) by Klein/Morelli at NASA-Langley



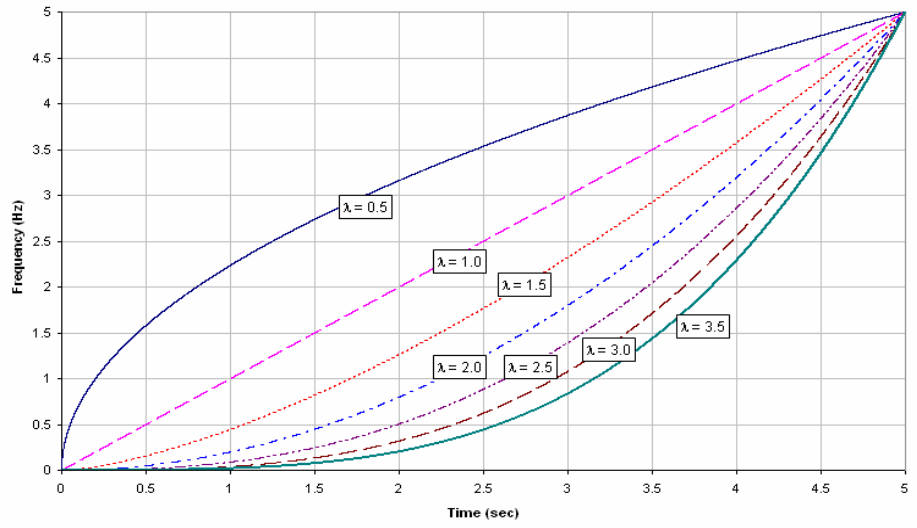
Pitch Chirp Training Maneuver

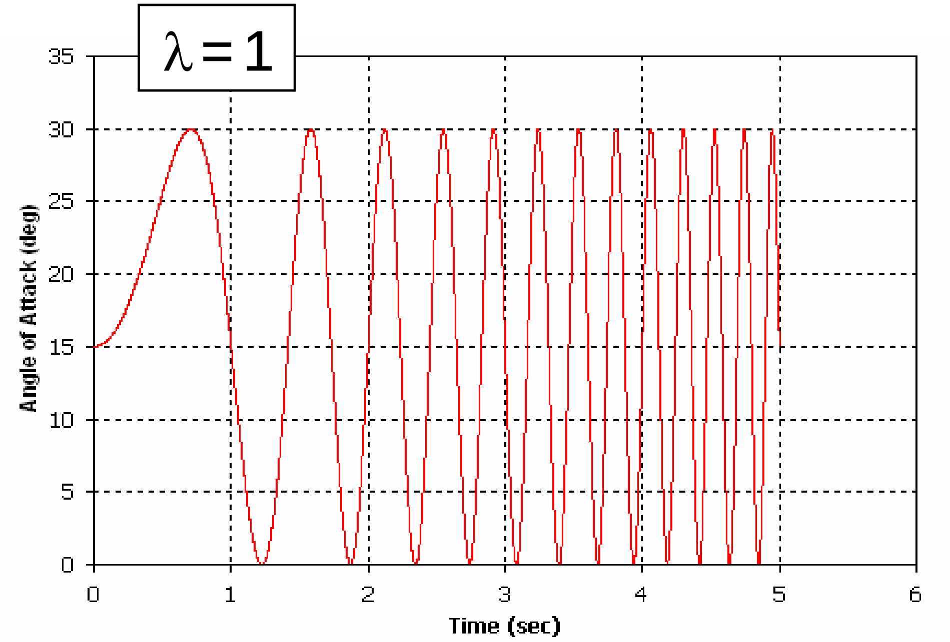
- Chirp Training Manuever:

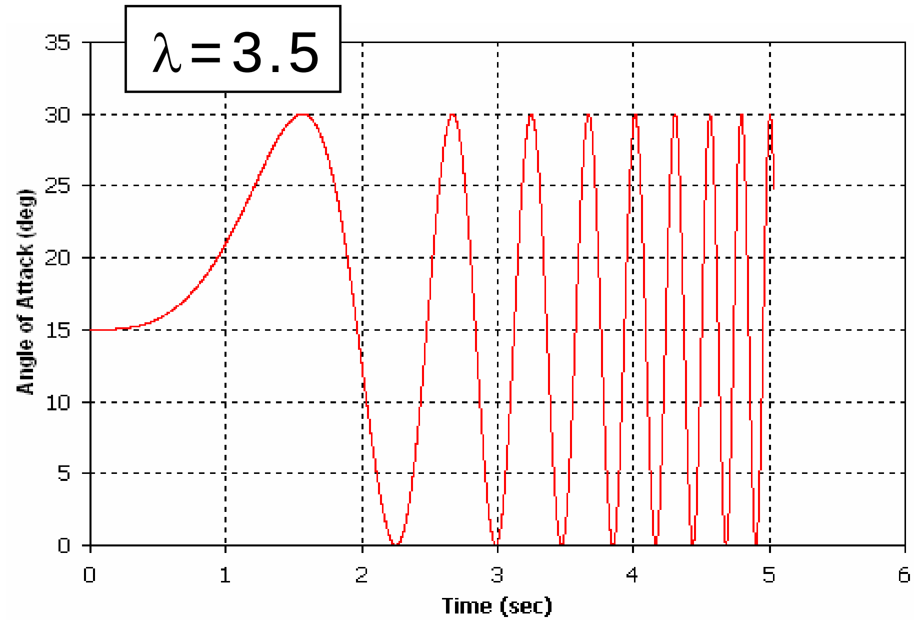
$$s(t) = \cos\left(2\pi\left(\frac{\beta}{\lambda+1}t^{\lambda+1} + f_1 t + \frac{\phi}{360}\right)\right)$$

$$\beta = \left(\frac{f_2 - f_1}{t_2^{\lambda}}\right)$$

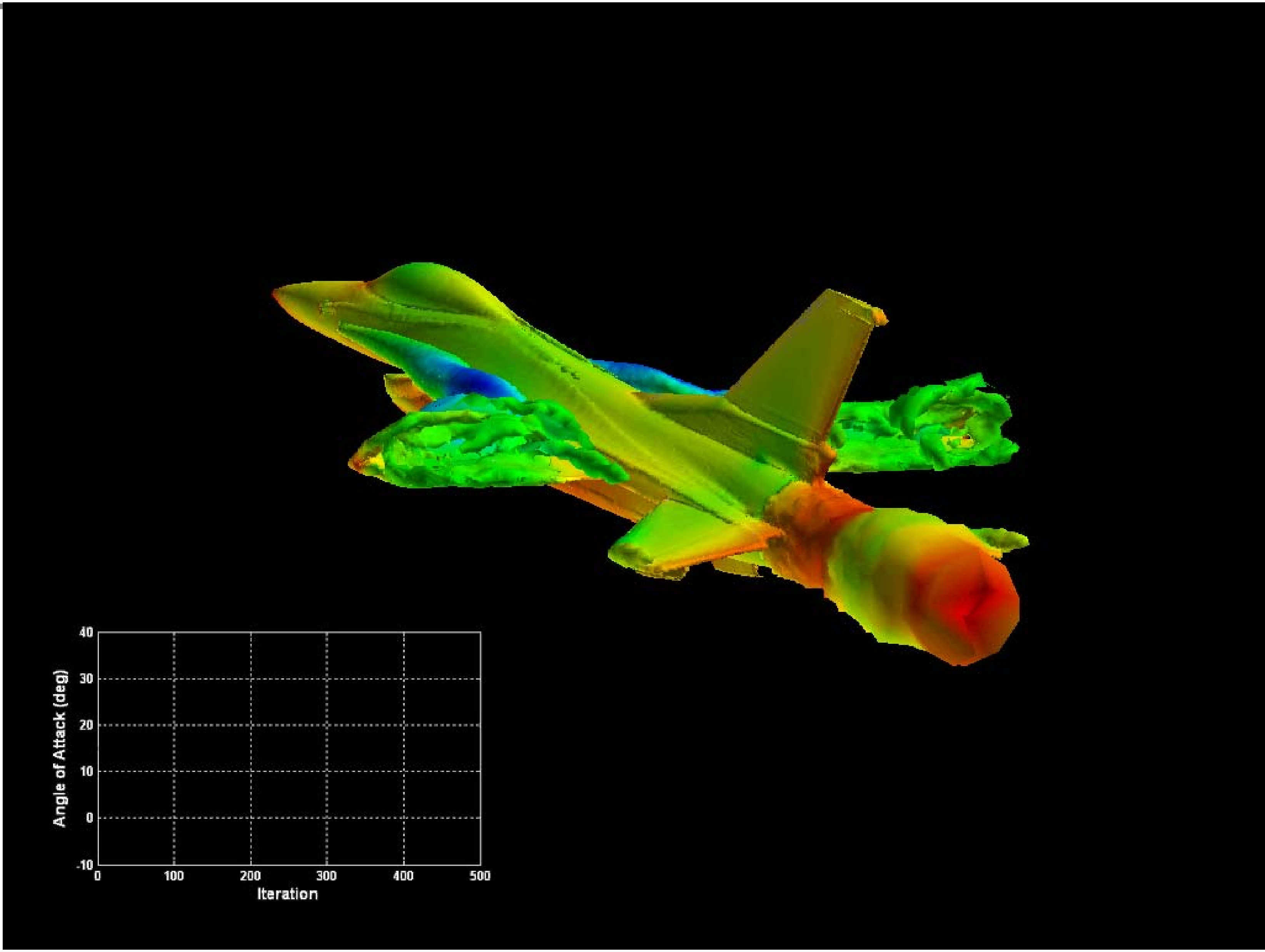
- Vary λ to dwell on the lower frequencies to capture static behavior







Pitch Chirp ($\lambda = 1.0$)



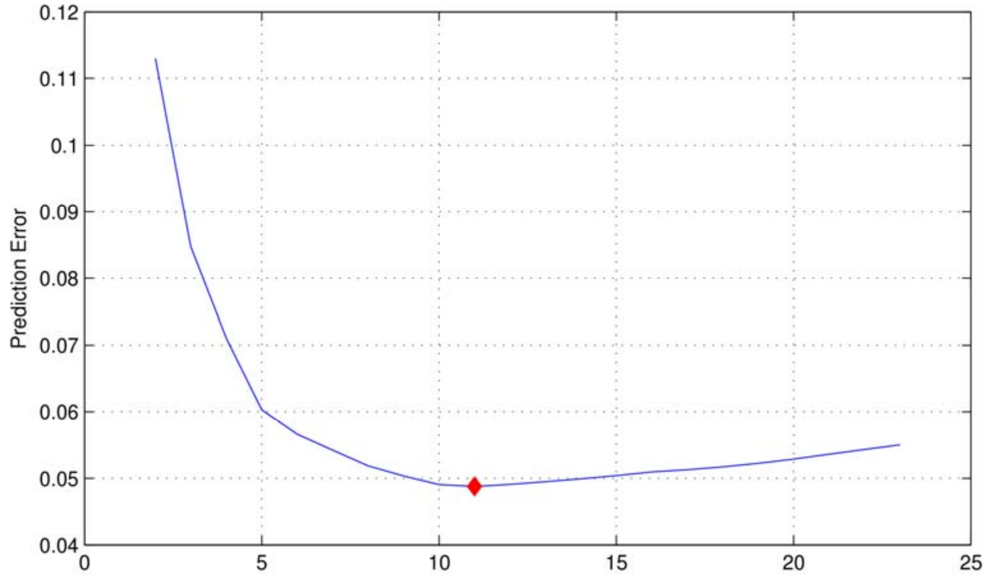
Play

SID of Pitch Chirp

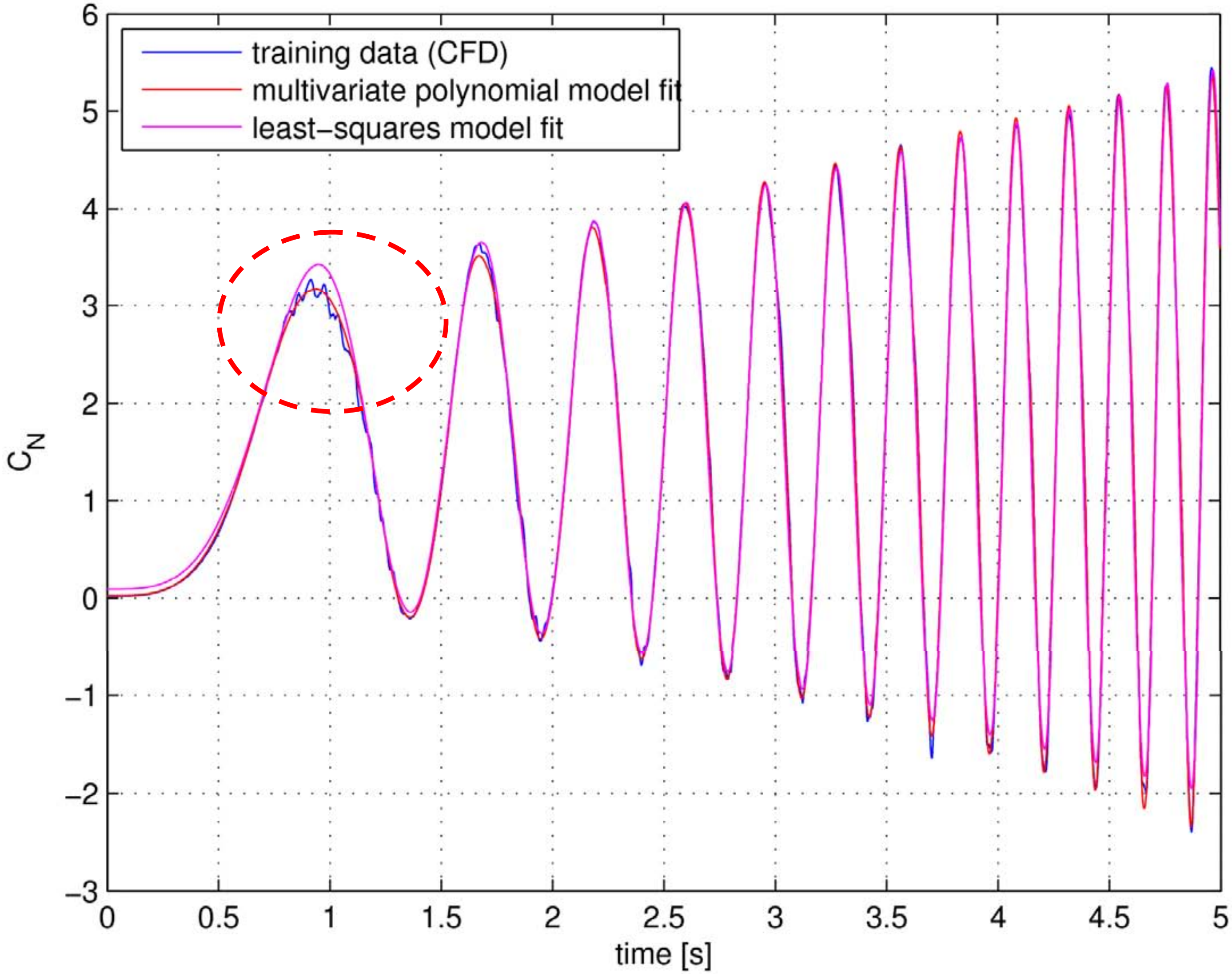
1. Least-squares linear model: $C_{N_{\text{lesq}}} = C_0 + C_{N_\alpha}\alpha + C_{N_q} q + C_{N_{\dot q}} \dot q$

2. Nonlinear multivariate polynomial model:
$$C_{N_{\text{mof}}} = C_0 + C_1\alpha + C_2 q + C_3\dot q + \ldots$$
$$+ C_4\alpha^2 + C_5\alpha^4 + C_6\alpha q^2 + C_7\alpha\dot q + \ldots$$
$$+ C_8 q\dot q + C_9 q^2\dot q + C_{10} q^3 + C_{11}\dot q^2$$

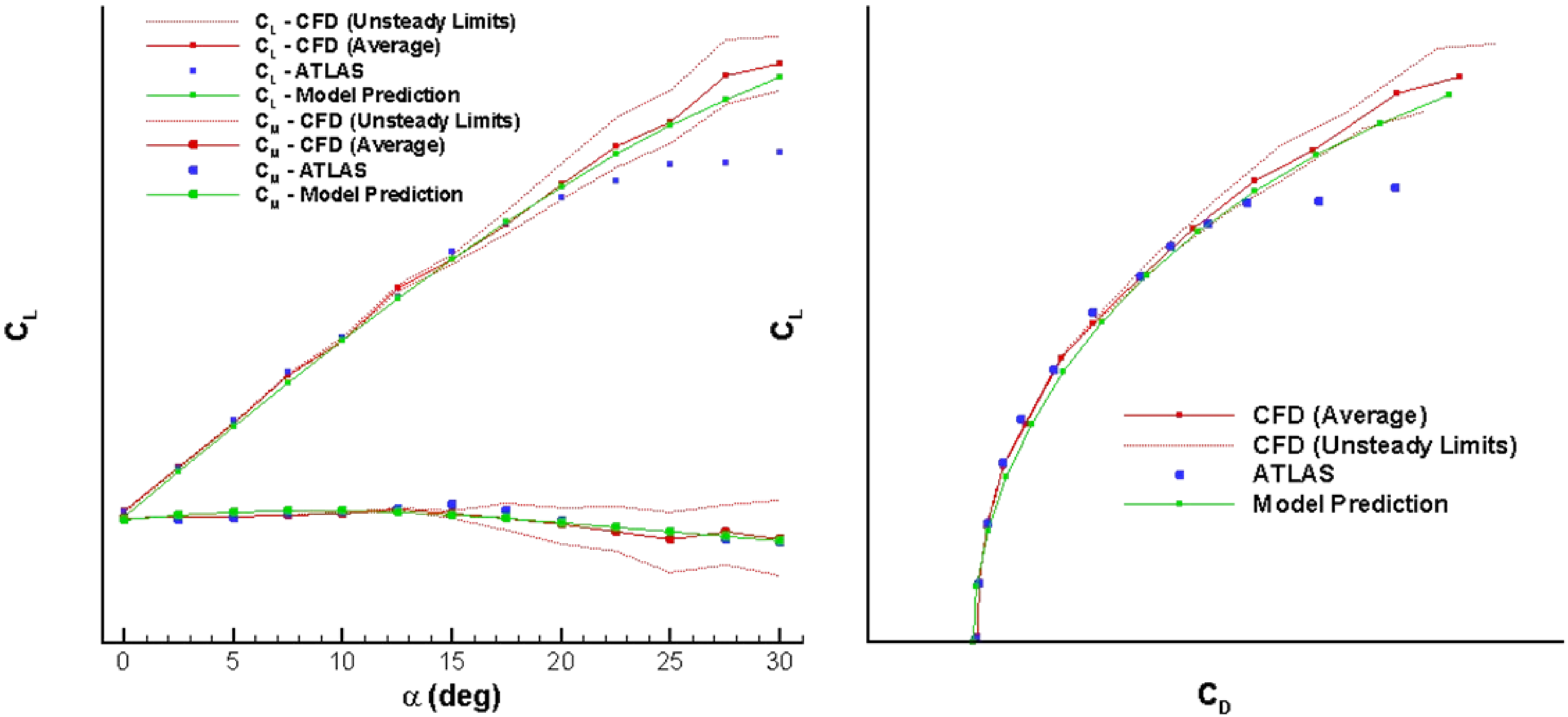
- Model structure determined using multivariate orthogonal functions generated by Gram-Schmidt orthogonalization, ordered by dynamic programming
- Retained modeling functions expanded into ordinary multivariate polynomial
- Parameters estimated using maximum likelihood technique



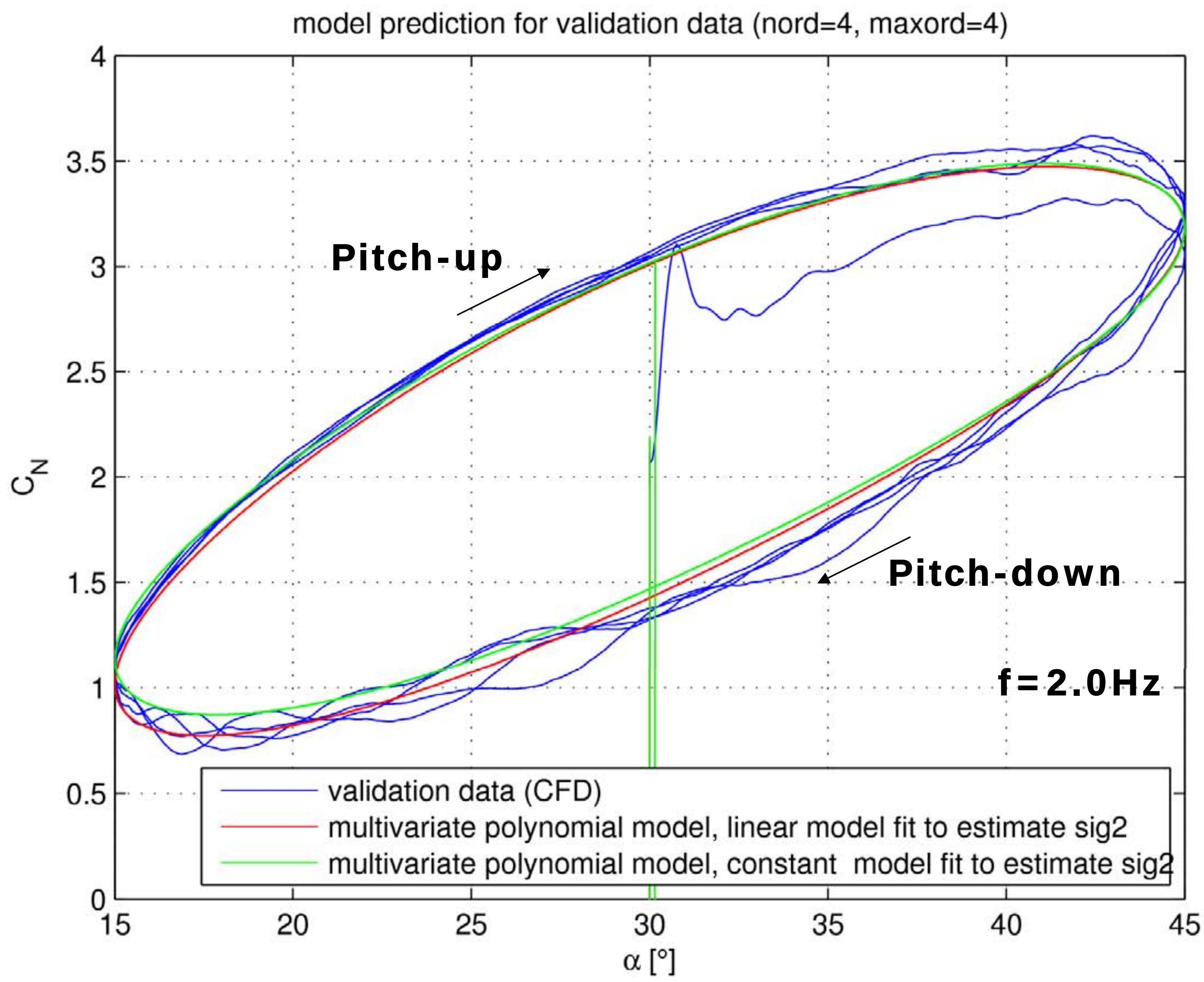
System ID of Pitch Chirp



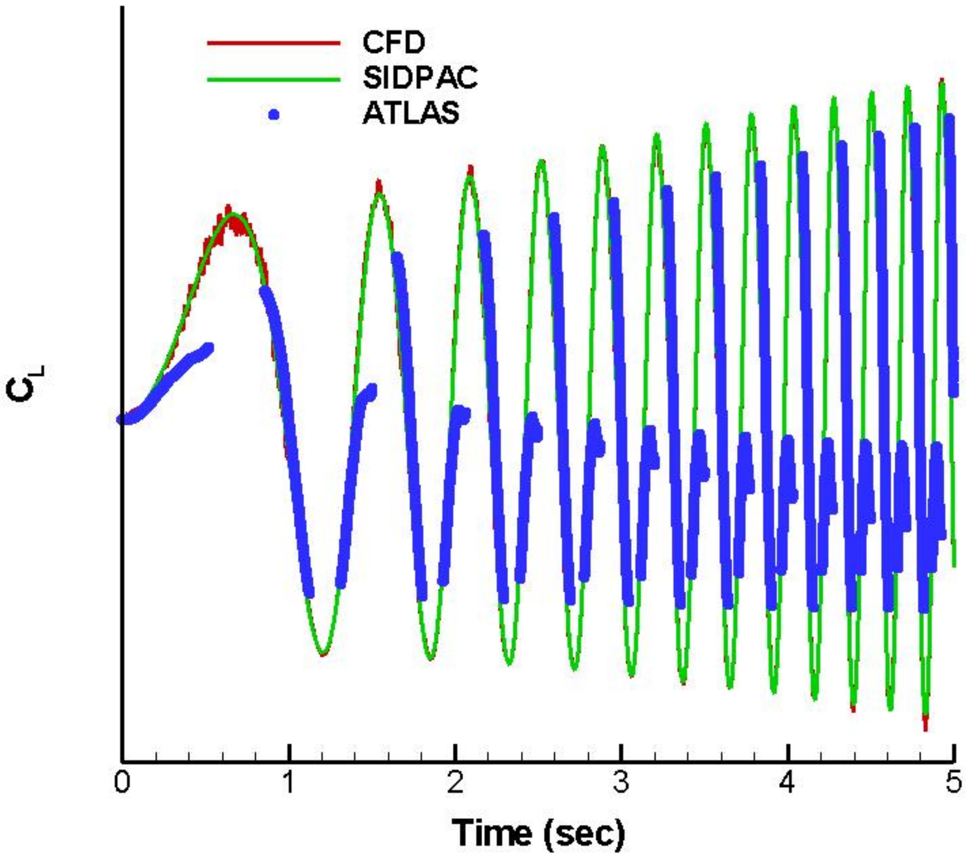
Static Validation vs. CFD / ATLAS

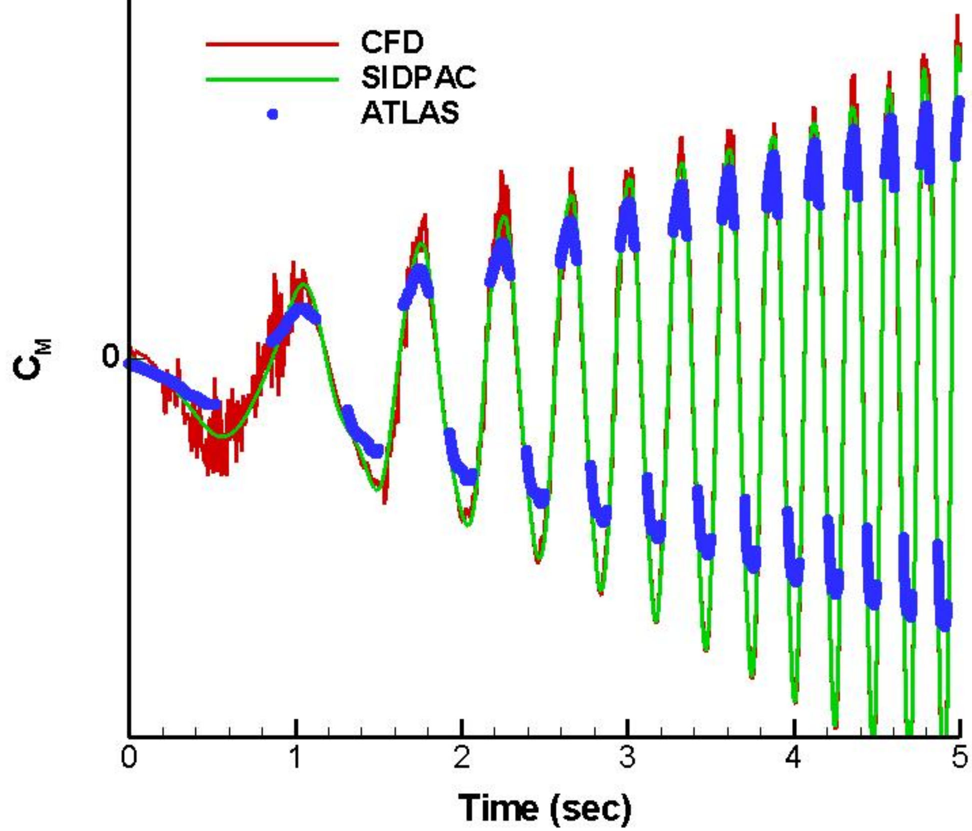


Dynamic Validation vs. CFD

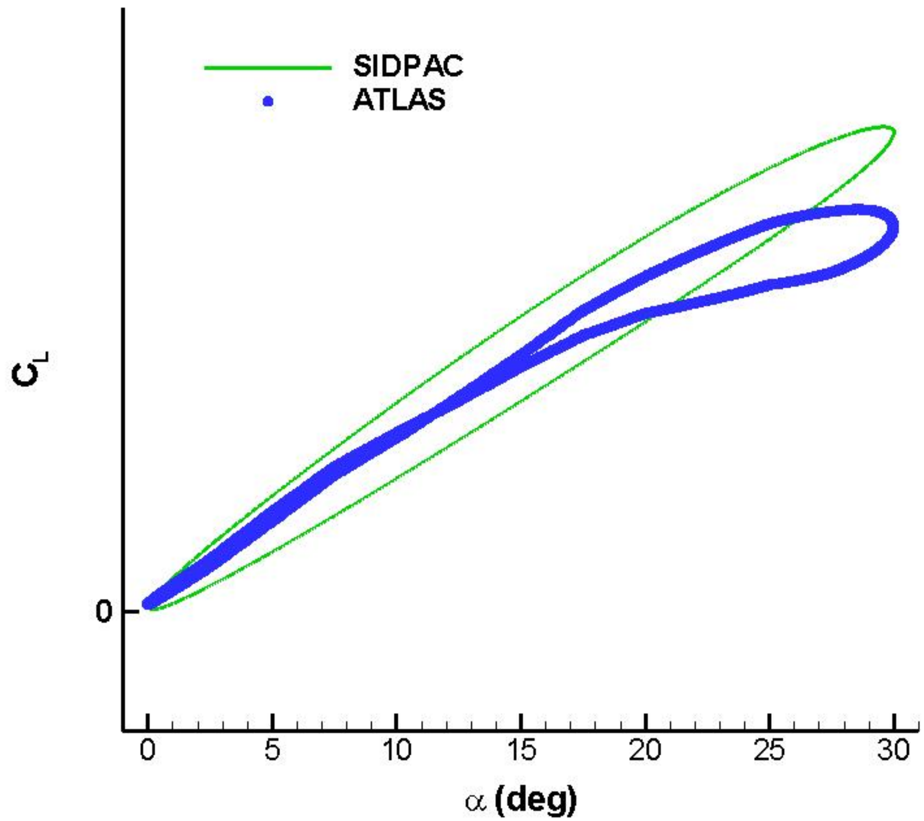


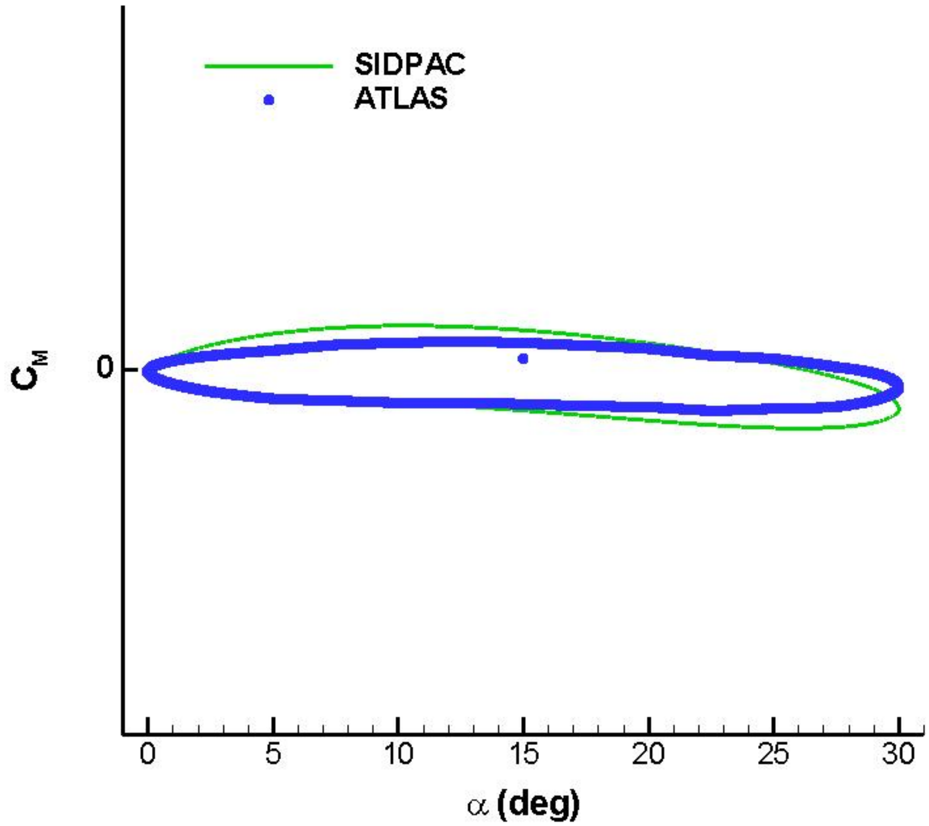
Dynamic Validation vs. ATLAS





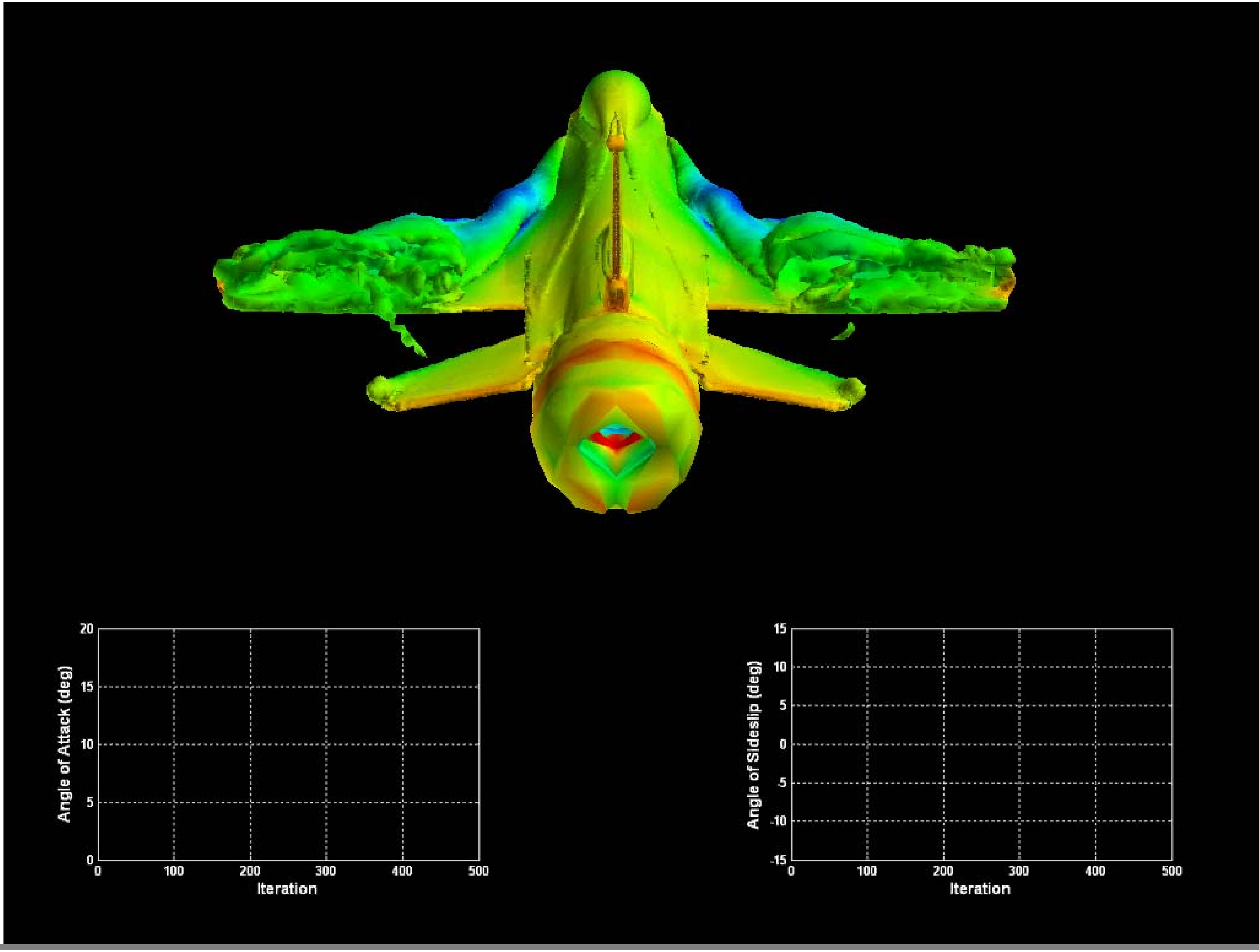
Dynamic Validation vs. ATLAS





1 Hz pitch oscillation about α = 15 deg

Yaw (λ=1.5)

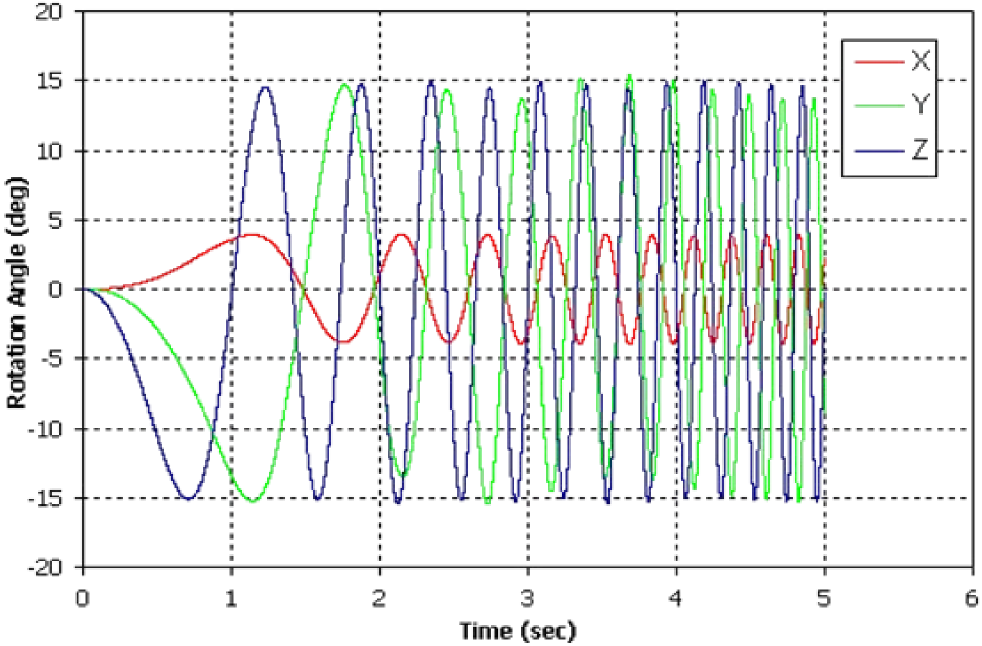


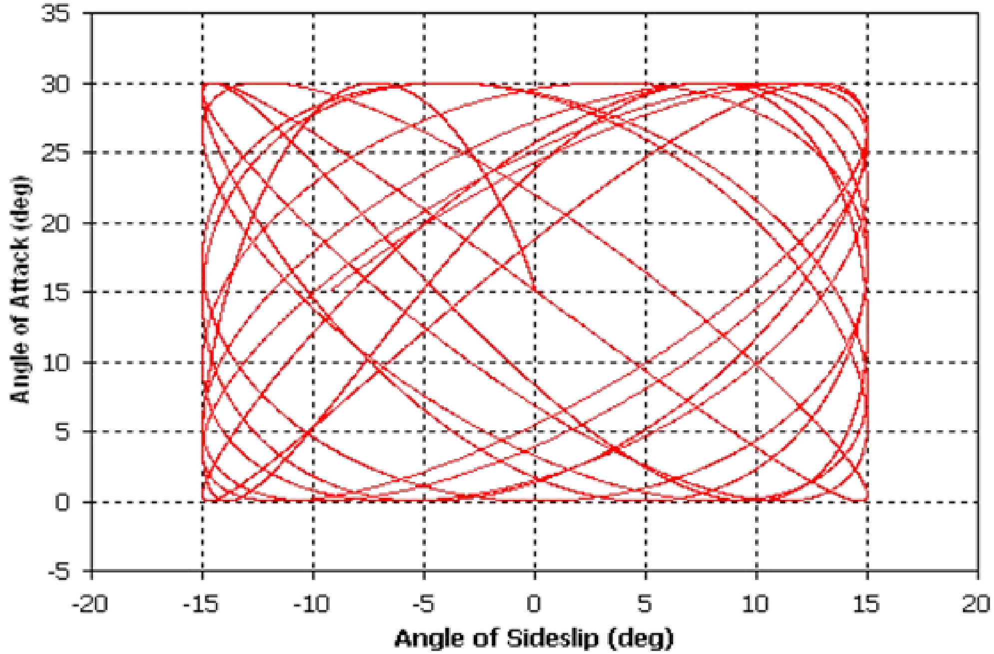
Angle of Attack (deg)
Iteration
Angle of Sideslip (deg)
Iteration

Play

Composite Pitch-Yaw Chirp

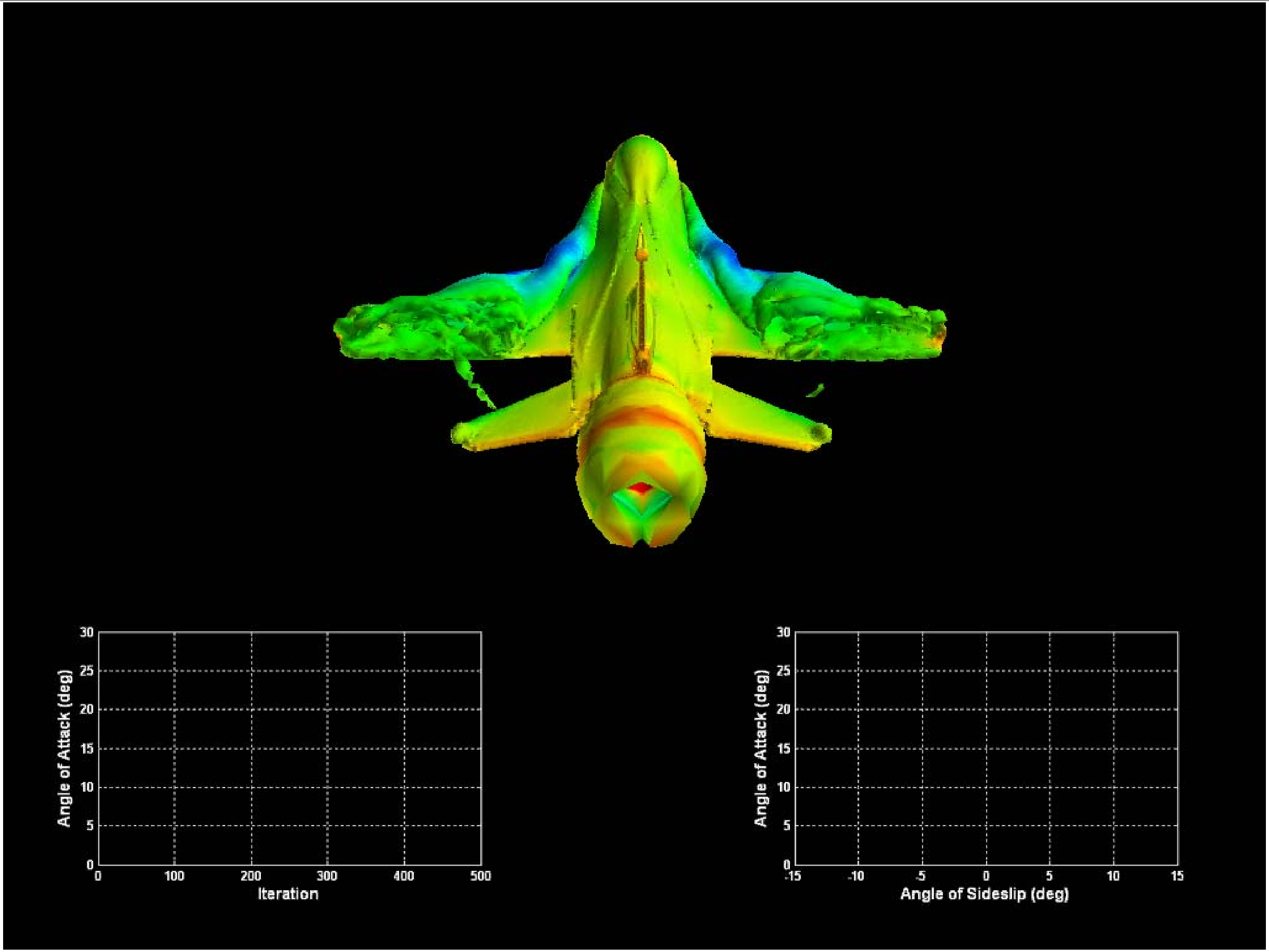
- Single motion input to create a model including motion about two axes → $\alpha = 15 \pm 15$ deg, $\beta = 0 \pm 15$ deg
- Input signals are made orthogonal by setting λ to 1.0 for pitch and varying λ until dot product of the two signals is zero resulting in λ of 1.47 for yaw signal





$$C_L(\alpha,\beta,p,q,r) = C_1 + C_2\alpha + C_3 q + C_4 p^2 + C_5\alpha q^2 + C_6\beta pq + C_7\beta p + C_8\alpha^2 q + C_9 r + C_{10}\alpha\beta^2 + C_{11}\alpha^3 + C_{12} pr + C_{13}\beta^2 p + C_{14}\beta^2 q + C_{15} p + C_{16}\beta^2$$

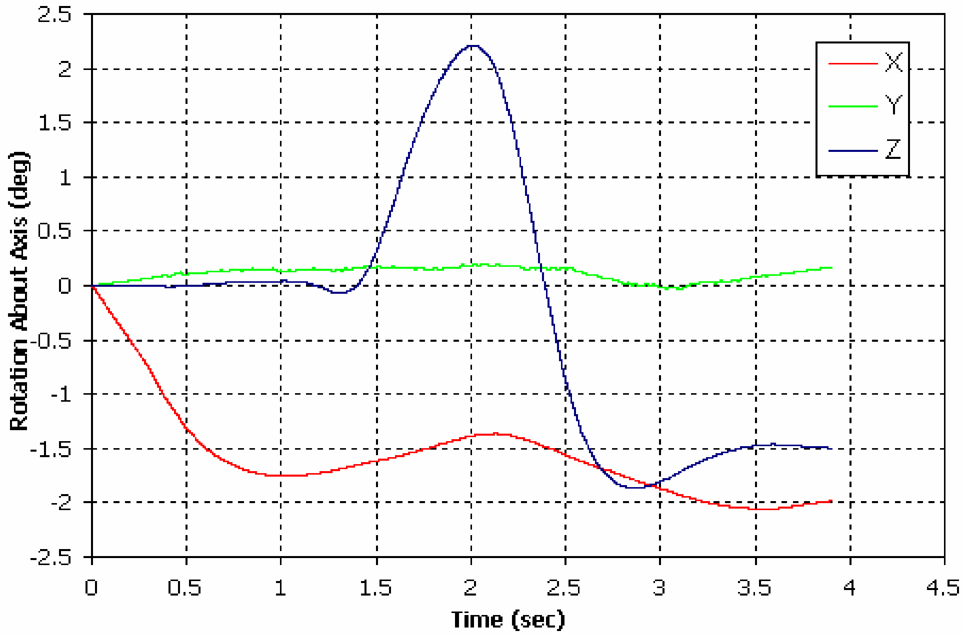
Composite Pitch-Yaw Chirp

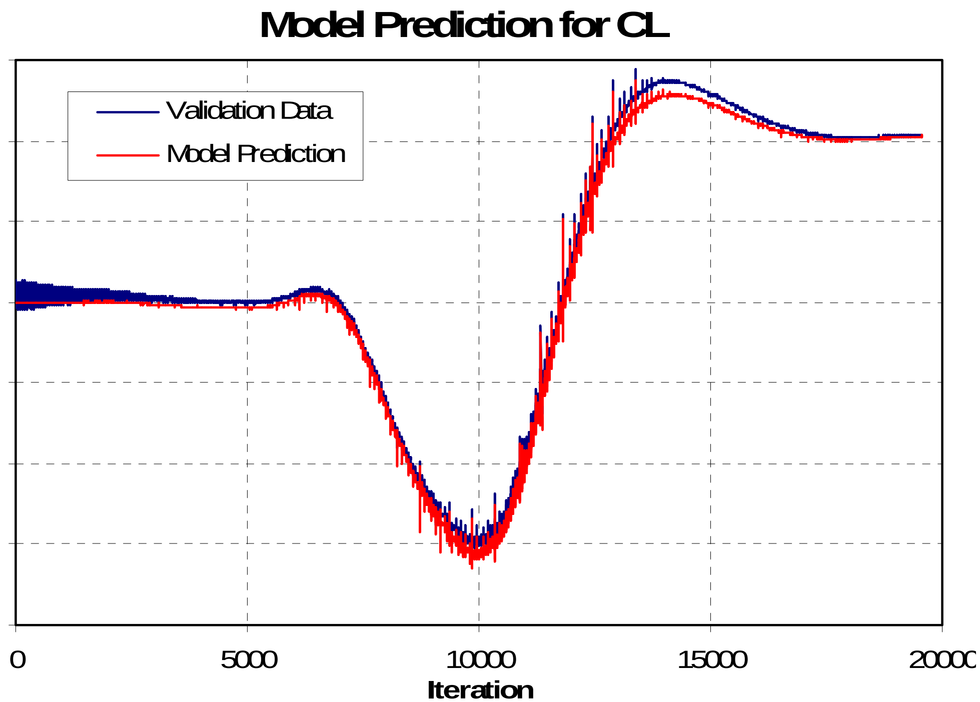


Play

Pitch Doublet Flight Test Maneuver

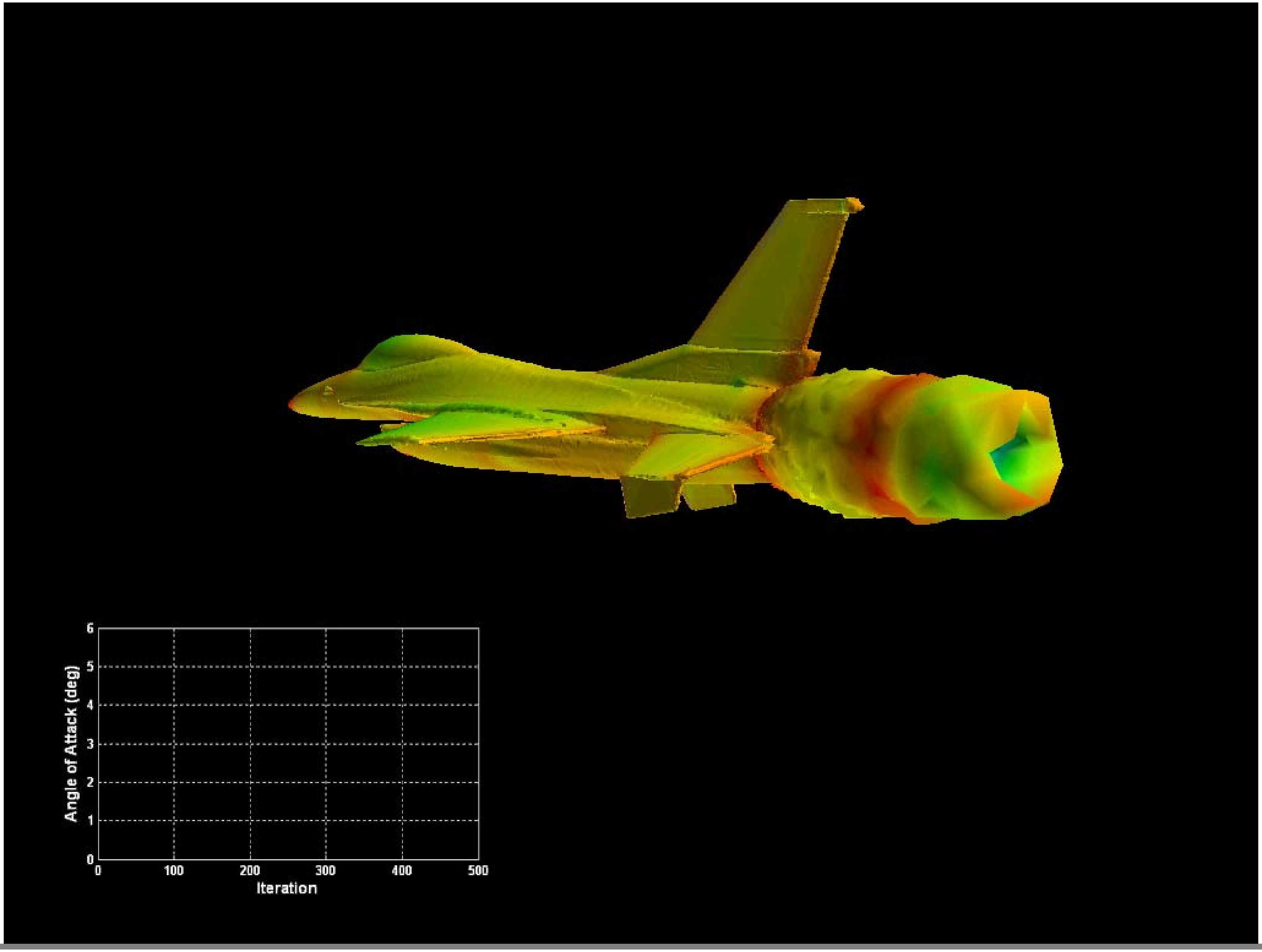
- Gathered actual strip chart data from a flight test
- Created the motion file that forces the F-16C through translations and rotations giving similar/same behavior
- Predict maneuver with reduced-order model and compare





Pitch Doublet Flight Test Maneuver

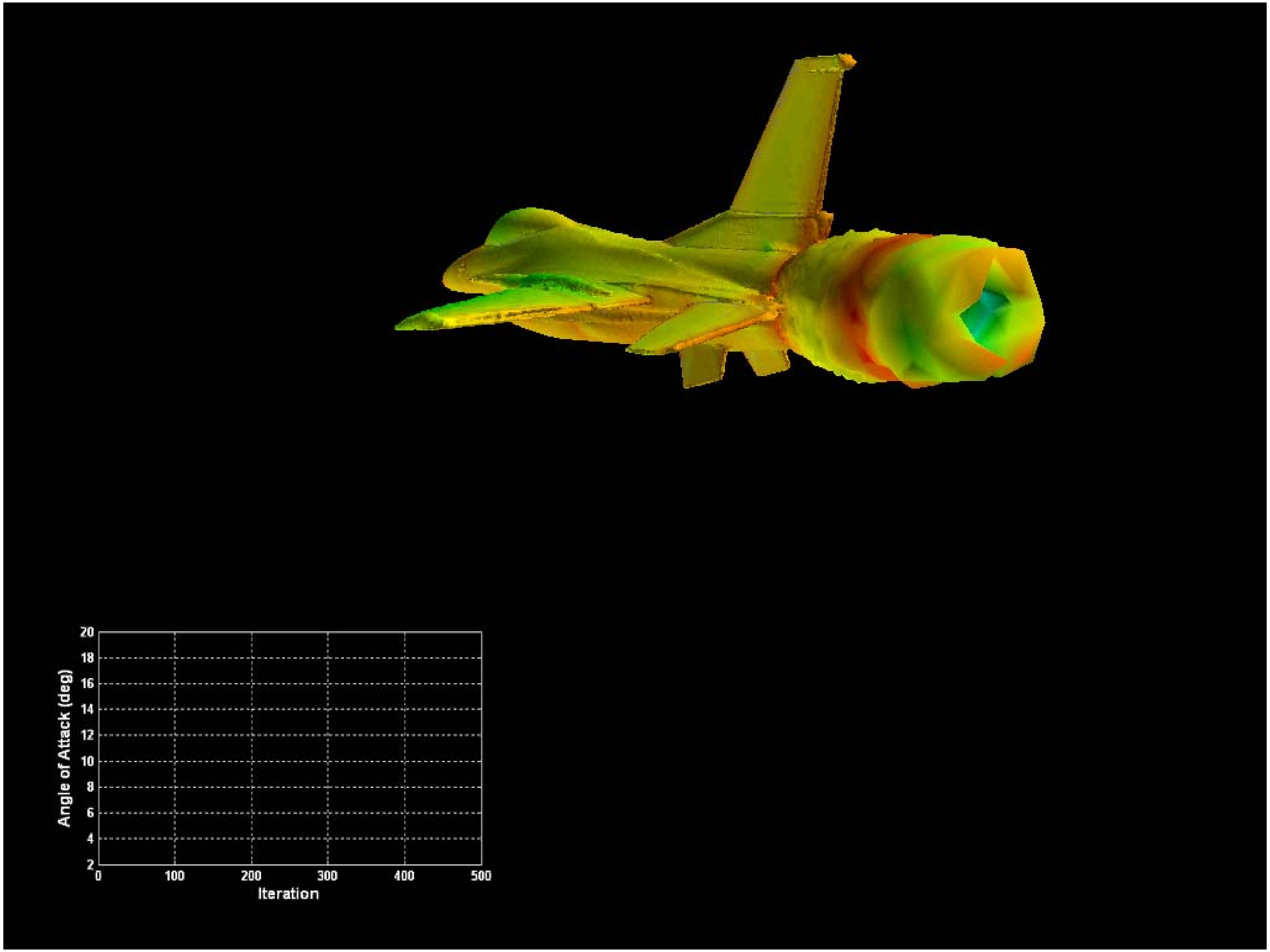
Simulation run at M=0.6 and h=5,000 ft with full span grid



Play

2.5g Wind-up Turn Flight Test Maneuver

Simulation run at M=0.6 and h=5,000 ft with full span grid



Play

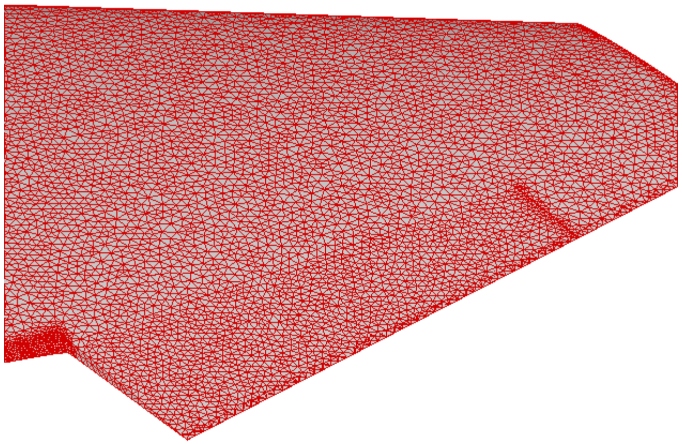
Conclusions and Ongoing Work

- State-of-the-art CFD techniques capable of predicting static, unsteady flow fields with complex aerodynamic behavior
- Motion+modeling technique shows promise and has many benefits
- Goal is to direct/complement experimental techniques – not replace them
- Need good full-aircraft S&C experimental data for validation (AVT-166)

<u>Ongoing Work:</u>

- More accurate F-16C grid with stores and pylons
- Comparison of CFD and model predictions with ATLAS/flight test data
- Integration of moving control surfaces and inclusion into the SIDPAC modeling process
- Investigation of range of validity of models across flight envelope
- Aeroelastic deformation

F-16C Trailing Edge Flaperon, ±30 deg



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Questions?